**Detrimental Effects of Effortful Physical Exertion on Cognitive Control in Younger and
Older Adults**

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Abstract

Research assessing the effects of age on physical actions and cognitive processes is often conducted in isolation. However, action and cognition often interact in daily functions and deteriorate with age. Therefore, assessing how motor actions affect core cognitive abilities and how age amplifies these effects is pivotal. The present study tested the effects of effortful physical exertion (isometric handgrip) on working memory (WM) and inhibitory control in young and older adults. Using a novel dual-task paradigm, participants engaged in a WM task with 0 or 5-distractors under concurrent physical exertion (5% vs 30% individual maximum voluntary contraction, MVC). Given our previous understanding that high physical exertion impairs inhibitory control, we hypothesized 1) inhibitory control of access to WM will be compromised under high physical exertion and 2) this effect will be amplified by age. Effortful physical exertion, although failed to affect WM accuracy with 0-distractors present for both age groups, reduced WM accuracy for the older, but not young adults, with 5-distractors present. Similarly, older adults experienced greater distractor interference with 5-distractors present under high physical exertion, indexed by slower reaction time (RT), confirmed by hierarchical Bayesian modeling of RT distributions. Our findings that a simple but effortful physical task may result in impaired cognitive control may be empirically important for understanding everyday functions of older adults. Reduced inhibitory control and physical abilities may pose a problem for older adults as the negative interactions between cognitive and motor tasks may impair daily functions and possibly increase the risk of injury.

Keywords: Working Memory, Inhibition, Cognition, Handgrip

Aging is inevitably associated with declines in various biological and mental functions, posing a challenge to the aging society (e.g., increased costs for societal care). Among these declines, older adults often experience a reduction in physical function and strength. Declines that accompany old age are not limited to physical function but include a reduction in key cognitive processes (e.g., working memory and recognition memory, Park & Reuter-Lorenz, 2009). Therefore, it is imperative to assess the effects of aging on physical and cognitive functions, along with their interaction.

In cognitive aging, the decline of cognitive abilities is apparent in some domains while remains intact in other domains. For example, crystalized abilities, typically acquired from overlearned knowledge, remain stable and even gradually improve throughout life (Harada et al., 2013). On the other hand, fluid abilities, which are abilities that involve processing, learning, and manipulating new information, typically decline with age (Harada et al., 2013). For instance, working memory (WM), a core cognitive process that maintains active information online in the service of ongoing mental activities (Cowan, 2001), declines steadily with age (Park & Reuter-Lorenz, 2009; Broockmole & Logie, 2013; Xie et al., 2019). Parallel to declining mental functions, physical functions also deteriorate with age, leading to increased amounts of time spent sedentary (Sparling et al., 2015) and reduced physical independence (Milanović et al., 2013). Sedentary lifestyles may be associated with age-related physiological changes, such as reduction in muscle mass and physical endurance. For instance, muscle mass and muscle strength, such as isomorphic handgrip strength, declines with age (Samuel et al., 2013; Kallman et al., 1990; Vandervoort, 2002). On average, healthy older adults' isometric strength is 20-40% weaker than younger adults (Vandervoort, 2002).

Although research assessing the effects of aging in relation to physical and cognitive processes is often conducted in isolation, action and cognition are often intertwined in daily functions (Leisman et al., 2016; Plummer-D'Amato et al., 2012). For example, when preparing a meal, one must consider the next physical and cognitive action needed to bring together the ingredients required and ensure that an accident does not occur, such as a stove-top fire. Recent literature has documented strong links between cognitive and motor functions (Leisman et al., 2016) in older adults. First, dual-task paradigms suggest that gait speed tends to decline in older adults while simultaneously walking and talking (Plummer-D'Amato et al., 2011) or simultaneously walking and performing a cognitive task (Plummer-D'Amato et al., 2012). Second, declines in physical strength can be accompanied by, and potentially preceded by (Taekema et al., 2012), declines in overall cognition in similar rates in aging (Praetorius Björk et al., 2016). Third, physical strength, such as handgrip strength, and gait can predict cognitive performance (Taekema et al., 2010) and socio-cognitive wellbeing (Blankevoort et al., 2013). Fourth, the effects of aging on physical and cognitive function can interact with each other, especially when executive function is involved in both domains (Leisman et al., 2016). For instance, WM performance declines can occur in older adults when a WM task is performed concurrently with a precision force tracking task requiring fine motor control and coordination than when the WM task is done in isolation (Voelcker-Rehage & Albers, 2007). Lastly, sedentary lifestyles in older adults have been associated with declines in fluid (Erickson et al., 2015) but not crystallized (Burzynska et al., 2020) abilities.

The close interactions between motor and cognitive functions can also manifest in young adults. For instance, engaging in a concurrent handgrip task during long-term memory encoding can impair later retrieval in young adults (Tomprowski et al., 2017). More importantly, task-

irrelevant distractors can more easily capture visual attention (Park et al., 2021) and get encoded into WM (Cappiello et al., 2018) under concurrent physical effort. These inhibition-based effects of physical effort provide an intriguing perspective to look at functional declines in older adults given the widely observed age-related declines in cognitive control. For instance, older adults are more susceptible to task-irrelevant visual stimuli suggesting age-related inhibitory failures in the presence of distracting information (Kramer et al., 1994). Reduced inhibitory regulation (i.e., ability to inhibit task-irrelevant information) and heightened distractibility, captured by the inhibitory deficit hypothesis, could account for age differences in WM (Hasher & Zacks, 1988). Therefore, age could amplify the negative effects of effortful physical action on concurrent cognitive function because of reduced inhibitory control in older adults. Given that many daily activities concurrently engage motor and cognitive functions, aging and age-related declines in inhibitory control and physical strength will pose a unique challenge to older adults.

The present study aimed to assess the interaction between motor and cognitive functions in young and older adults by testing the effects of concurrent effortful physical action on key cognitive functioning. Note, these effects can show different characteristics and are supported by different mechanisms in comparison to the effects of acute or habitual physical activity (Pontifex et al., 2019; Erickson et al., 2015). Specifically, we assessed the impact of simple physical exertion through an isometric hand dynamometer on WM and inhibitory control using a novel dual-task paradigm, where participants engaged in a WM task under effortful physical exertion. In the WM change detection task, participants were instructed to remember three briefly presented task-relevant orientation bars in red, with 0 or 5 task-irrelevant bars in blue (*0-distractor* vs. *5-distractors* conditions), in the memory array. After a short delay interval, participants reported whether the three task-relevant orientation bars changed orientation, or not,

from memory to test. Physical load was operationalized as handgrip force exertion at different subject-specific maximum voluntary contraction (MVC, 5% versus 30%), independent of individual differences in muscular strength and fitness level. Given that high physical load impairs inhibitory control (Park et al., 2021), it is hypothesized that 1) inhibitory control of access to WM will be compromised under high physical load and 2) this effect will be amplified by age. Accordingly, it was predicted that 1) worse performance in the WM task will manifest in the 5-distractor condition than the 0-distractor condition under high physical load, but similar performance between the two distractor conditions under low physical load; and 2) this two-way interaction will be more pronounced in the older adults than younger adults, yielding a significant three-way interaction.

In testing these predictions, we assessed WM task performance using an accuracy-based measure, Cowan's K (representing the number of items successfully encoded in WM, Cowan, 2001; see Data Analysis), as well as a speed-based measure, reaction time (RT). Analyzing RT alongside accuracy provides some advantages in testing the effect of concurrent physical effort on WM. First, RTs can capture moment-by-moment fluctuations in WM processes with continuous estimates. Second, the distributional characteristics of RTs could reveal underlying cognitive processes for various experimental effects (Balota & Yap, 2011; Hohle, 1965). For instance, to account for the mixed findings regarding the effect of physical effort on cognition (i.e., positive versus negative effects, McMorris et al., 2011), Park and colleagues (2021) postulated that two opposite effects may coexist and possibly cancel each other out in single point estimates of RTs (e.g., mean RTs). Specifically, they used a computational measurement model, the *ex-Gaussian* model (a convolution of Gaussian function with μ and σ parameters and exponential function with τ parameter), to assess dissociable effects of physical load on a

concurrent attention task in a handgrip and attention dual-task paradigm. They found that the RT benefit was universal across the RT distributions (i.e., faster responses captured by the ex-Gaussian μ parameter), presumably reflecting effort-mediated phasic arousal (Aston-Jones & Cohen, 2005; Davranche et al., 2006), whereas the RT cost was present exclusively at the slowest portion of RTs (i.e., infrequent but delayed responses, captured by the ex-Gaussian τ parameter). Adopting Park and colleagues' (2021) approach, the present study will identify the origin of the detrimental effect of concurrent physical effort on WM function and how it manifests in different manners between younger and older adults.

Methods

Participants

A priori power analysis for mixed-effect repeated-measures analysis of variances (ANOVA) suggests that a total sample size of 36 participants ($N = 18$ for each age group, with 4 repeated-measured conditions) would provide 80% statistic power for a significant mixed-effect interaction at a medium level ($F = 0.25$, Faul et al., 2009). To ensure sufficient statistical power, 31 undergraduate students (56.3% female; $M_{\text{age}} = 20.37$, $SD_{\text{age}} = 2.27$) from University of California, Riverside and 19 older adults (47.4% female; $M_{\text{age}} = 72.37$, $SD_{\text{age}} = 5.04$) from local communities were recruited. All participants reported normal or corrected-to-normal vision and normal color vision. None of the participants reported a history of major neurological (e.g., mild cognitive impairment, dementia, or stroke), psychiatric (e.g., mood disorders or schizophrenia), or medical (e.g., diabetes, HIV, or drug abuse) conditions. Additional data from three young and three older adults were excluded from the study due to unsuccessful handgrip recordings resulting from misuses of the hand dynamometer or arthritis.

The experimental procedure was approved by the Institutional Review Board of University of California, Riverside. All participants were provided written informed consent and were compensated for their participation by course credits (undergraduate participants) or \$20/hour (older adults).

Procedure

Stimuli were presented on an LCD monitor with a grey background (6.1 cd/m^2), using PsychToolbox-3 (Brainard, 1997) for Matlab (The Math Works, Cambridge, MA) at a viewing distance of 57 cm. The monitor was calibrated with an X-Rite I1Pro spectrophotometer (X-Rite, Inc., Grand Rapids, MI). Participants' grip force was measured using an isometric Vernier HD-BTA hand dynamometer (Vernier, Beaverton, OR). Each participant first completed a brief assessment to obtain isometric maximum voluntary contraction (MVC) of grip force and then a visual WM task with concurrent handgrip at different levels of %MVC.

MVC Measurement

At the beginning of the experimental session, participants were instructed to hold the hand dynamometer in their left hand using maximum force for 4,000ms with no visual feedback. This procedure was repeated 3 times. The median grip force level during the last 2,000ms of the 4,000ms measurement window was averaged across the trials as the MVC of each participant. Participants then practiced across 10 trials to control their grip force level at 5%, 30%, or 65% MVC for 4,000ms, with real-time visual feedback of the exerted grip force, indicated by a red visual gauge of the exerted force proportional to their %MVC (Figure 1).

Concurrent Handgrip and WM Dual-Task

Next, in the concurrent handgrip and WM dual-task (Figure 1), each trial began with a screen prompting participants to initiate a left-handgrip on the hand dynamometer at or slightly

above 5% or 30% of their MVC. During the initial 4,000ms, real-time visual feedback of the exerted grip force was provided similar to the practice handgrip trials. No visual feedback of force exertion was provided afterwards. Yet, participants were required to maintain the level of the required hand force throughout the visual WM change detection task until they made a response. To be considered as a successful trial, participants should exert their hand strength no less than 3% but no greater than 10% MVC in the 5% MVC condition and no less than 25% but not greater than 35% MVC in the 30% MVC condition for more than two-thirds of the time during the visual WM task. As kinesthetic information (Ángyán et al., 2005) could be sufficient for subjective estimation of the exerted force with minimal WM load (Lowe, 2016), participants were able to successfully hold the handgrip at or slightly above the required hand strength level (96.73% overall handgrip accuracy), despite no real-time visual feedback. Yet, it was not surprising that participants could more successfully exert hand strength at 5% MVC (98.69% handgrip accuracy) than 30% MVC (94.72% handgrip accuracy), $t(49) = 3.33, p = .002$. However, there is no significant age effect in this difference, $t(48) = -0.27, p = .792$. The subsequent analysis of WM task performance will primarily focus on the trials when participants successfully exerted hand force to the required level during the WM task.

While participants were maintaining their hand force at the required level of %MVC, they performed a visual WM task. In this task, a memory array consisting of orientation bars appeared for 100ms. On half of the trials, this memory array displayed 3 red rectangular bars, while on the other half of the trials, this memory array displayed 3 red rectangular bars with 5 blue rectangular bars. These rectangular bars (5° by 1° of visual angle in size) were randomly oriented horizontally, vertically, or diagonally, and were presented at randomly selected centers within a 3-by-3 grid of an 11° -by- 11° area in visual angles. Participants were required to only

remember the orientation of the 3 red rectangular bars while ignoring any blue bars, making it a visual WM task of set size 3 with either 0 or 5 distractors. The memory array was followed by a 900ms delay interval with a blank screen containing a central fixation point, after which a test array appeared and remained on screen for 2,000ms. On half of the trials, this test array was identical to the memory array, while on the other half of the trials, one of the red orientation bars tilted either 45 or 90 degrees. Participants were instructed to use their right index and middle fingers to press buttons on a Logitech Precision gamepad to indicate whether the test array was the same or different from the memory array, respectively, within a 4,000ms maximum response time window. Accuracy of the change detection responses was emphasized over speed. All experimental factors including low versus high physical loads, 0 versus 5 distractors, and change versus no change trials were randomly intermixed in each experimental block of 16 trials. The full experiment consisted of 10 blocks, yielding a total of 160 trials. These experimental trials were preceded by 1 block of 12 practice trials.

Data Analysis

Participants' change detection performance for task-relevant items was measured as Cowan's K , $[(\text{hit rate} - \text{false alarm rate}) * N]$ (Cowan, 2001), where N is the task-relevant set size (i.e., 3). Higher Cowan's K values reflect a greater number of task-relevant items retained in visual WM. A 2 (younger adults vs. older adults) x 2 (0-distractor vs. 5-distractor) x 2 (5% vs. 30% MVC) mixed-effect repeated-measures ANOVA was performed on K for correct handgrip trials to investigate age-related differences across distractor and physical exertion conditions. To evaluate dual-task effects, only trials where participants' exerted grip force reached the indicated level of MVC during the WM change detection task were included for these analyses.

In addition, RT analyses were performed for correct handgrip trials. An outlier rejection for extremely short ($< 200\text{ms}$) or long ($> 10,000\text{ms}$) RTs was conducted, resulting in 33 out of 8080 total trials rejected (0.41%). For RT distributional analyses, we modeled correct RTs with ex-Gaussian function for each condition and each participant, under the hierarchical Bayesian approach developed by Park and colleagues (2021). This method (see Supplemental Method) produces the mean of the posterior distribution (from 20,000 MCMC samplings after 20,000 warming-up) and the interval containing 95% of the posterior distribution (95% highest density interval, HDI; Kruschke, 2011), which can be treated as a point estimate and as an analogue of a frequentist confidence interval, respectively. When making a statistical inference, the HDI can serve as the strength of evidence, thus one can reject the null hypothesis if the positive or negative side of 95% HDIs for the difference between conditions do not cross over zero (Kruschke, 2014).

Results

Characteristics of the Current Sample

Sample demographics for younger ($N = 31$) and older ($N = 19$) adults are shown in supplementary Table 1. While previous studies reported attenuated MVC in older adults (Samuel et al., 2013; Vandervoort, 2002), we did not observe a significant age difference in MVC in our sample, $t(48) = -0.60$, $p = .555$. Yet, this is unlikely due to the insensitivity of the MVC measure in the present study, as MVC was higher for men ($M = 168.92$, $SD = 64.71$) than women ($M = 139.49$, $SD = 58.08$) across both age groups, $t(47) = 4.51$, $p < .001$. Considering that physical load in the present study is manipulated as %MVC, the potential effects of the presence (or absence) of individual and group differences in physical strength manifested as MVC are largely removed. We also did not observe a significant difference in the likelihood of successful hand

strength maintenance during the visual WM task between younger ($M = 97.07$, $SD = 3.91$) and older ($M = 96.31$, $SD = 4.66$) adults during the change detection task, $t(47) = -0.56$, $p = .577$.

Visual WM Change Detection Performance Under Concurrent Physical Load

Of primary interest, we investigated Cowan's K across experimental conditions and age groups in successful handgrip maintenance trials, based on a three-way mixed-design repeated-measures ANOVA with age group (younger vs. older adults) as a between-subject factor and distractor size (0 vs. 5) and physical effort (5% vs. 30% MVC) as within-subject factors.

Consistent with the effects of distractor size commonly observed in visual WM literature, distractor size has a significant main effect on Cowan's K for task-relevant items, $F(1, 49) = 56.83$, $p < .001$, $\eta^2_p = .54$. Observers remembered more task-relevant items under the 0-distractor condition ($M = 2.46$, $SD = 0.46$) compared to the 5-distractor condition ($M = 2.19$, $SD = 0.60$). Furthermore, there was a significant main effect of age, $F(1, 49) = 89.81$, $p < .001$, $\eta^2_p = .65$, such that young adults remembered more task-relevant items ($M = 2.50$, $SD = 0.20$) than the older adults ($M = 1.84$, $SD = 0.39$).

Although the main effect of physical effort on change detection performance was not statistically significant, $F(1, 49) = 0.07$, $p = .786$, $\eta^2_p = .00$, there was a significant three-way interaction, $F(1, 49) = 6.86$, $p = .012$, $\eta^2_p = .12$. To further evaluate this interaction, we performed separate two-way mixed-effect ANOVAs in young and older adults when distractors in the visual WM task were present or absent (i.e., 5- vs. 0-distractor conditions, respectively). When distractors were present, there was a significant interaction between age-group and concurrent physical load on Cowan's K , $F(1, 49) = 10.19$, $p = .002$, $\eta^2_p = .17$. Older adults retained fewer task-relevant visual WM items under high physical load ($M = 1.49$, $SD = 0.49$), in comparison to low physical load ($M = 1.72$, $SD = 0.43$), $t(18) = 2.32$, $p = .032$; Figure 2A). A similar pattern

however was not statistically significant in young adults, $t(31) = -1.92, p = .065$. Furthermore, when distractors were not present in visual WM, we did not observe a significant interaction between age-group and concurrent physical load on Cowan's K , $F(1, 49) = 0.33, p = .568, \eta^2_p = .01$. In other words, the extent of distractor interference (i.e., Distractor Present–Absent) on WM was comparable in young adults across physical load conditions but for older adults, especially when distractors were present (Figure 2B).

Collectively, these results suggest that effortful physical exertion profoundly compromised the inhibition of task-irrelevant information in older adults compared to young adults. In contrast, physical effort had no significant effect on WM performance for either age group when distractors were absent. Consequently, older adults would find it hard to remember task-relevant items when distractors were present in WM under a higher concurrent physical load.

Reaction Time Effects of Concurrent Physical Load

Following the analyses on Cowan's K , a three-way mixed-design repeated-measures ANOVA for the RTs (Figure 3A) was performed with two within-subject factors, distractor size (0 vs. 5), and physical effort (5% vs. 30% MVC), and a between-subject factor, age group (younger vs. older adults). There were significant main effects of all three factors; for distractor size, $F(1, 49) = 82.99, p < .001, \eta^2_p = .63$, for age, $F(1, 49) = 19.61, p < .001, \eta^2_p = .29$, and for physical load, $F(1, 49) = 4.66, p = .036, \eta^2_p = .09$. The main effects of distractor size and age group are conceptually in the same direction (i.e., worse performance) as the results of Cowan's K estimates. Specifically, participants' RT for the visual WM task was slower when task-irrelevant distractors were present and in older adults than younger adults. However, physical load yielded an opposite effect as the one for Cowan's K . Specifically, RT was significantly

faster under high physical effort ($M = 895.5$ ms, $SD = 270.30$ ms) compared to low effort ($M = 917.00$ ms, $SD = 288.50$ ms).

The opposite RT effects, the RT-facilitation effect of physical effort versus the RT-interference effects of distractor size and age group, could cancel each other out and attenuate the interaction effects of these factors, in line with the findings from Park and colleagues (2021). Accordingly, the three-way interaction was marginally significant, $F(1, 49) = 3.41$, $p = .071$, $\eta^2_p = .07$. However, separate two-way mixed-effect ANOVAs for each distractor size condition revealed an apparent asymmetry in the age-by-physical effort interaction, which was significant in the distractors present condition, $F(1, 49) = 4.18$, $p = .046$, $\eta^2_p = .08$, but not in the distractor absent condition, $F(1, 49) = 0.05$, $p = .817$, $\eta^2_p = .00$. In other words, the extent of RT delay due to distractor interference (i.e., Present – Absent) was comparable across all age groups and physical load conditions, except when older adults were presented with the distractors under the higher physical effort (Figure 3B).

Hierarchical Bayesian ex-Gaussian Analyses for Reaction Times

To further explore the nature of these opposite effects on mean RTs, we assessed whether these effects manifested on different aspects of the RT distributions, captured by our hierarchical Bayesian ex-Gaussian model, in a dissociable way. The group-level posterior mean and 95% HDI for each ex-Gaussian parameter (μ and σ for the Gaussian component and τ for the exponential component) as a function of age, distractor size, and physical effort are summarized in Table 1.

We reconstructed the three-way interactions for each parameter by taking the differences across conditions (i.e., the difference between age group [older – younger] of the difference between physical effort conditions [30% MVC – 5%MVC] of the difference between distractor

size conditions [5-distractor – 0-distractor]; Figure 4). The resulting posteriors revealed a distinctive, opposite pattern between μ (-72.8ms, 95% HDI [-127.6ms, -24.0ms]) and τ (+127.7ms [+61.9ms, +201.7ms]), whereas no reliable effect was observed in σ (-19.1ms [-60.1ms, +18.0ms]). Specifically, the three-way interaction in μ primarily manifested in a negative direction (i.e., RT benefit). On the contrary, the three-way interaction in τ was largely positive (i.e., RT cost). The bi-directional interaction effects on μ and τ indicate that, when irrelevant distractors were present under higher handgrip force exertion, older adults' responses were generally faster (captured by smaller μ), but at the expense of reduced inhibition of distractors which in turn resulted in an extreme delay (i.e., the slowest portion of the distribution, captured by greater τ).

Discussion

The present study investigated the effects of effortful physical exertion on cognitive control of accessing WM in younger and older adults. Effortful physical exertion (30% versus 5% MVC), although failed to affect WM accuracy at the 0-distractor condition for either age group, reduced WM accuracy for the older adults, but not young adults, at the 5-distractor condition. In other words, older adults were less likely to inhibit distracting information when engaging in an effortful physical task. Similar 3-way interactions were found for mean RTs and Hierarchical Bayesian ex-Gaussian Analyses of RT components in the WM task. In particular, reduced inhibition in older adults, but not young adults, under the 5-distractor and higher exertion conditions manifested as a delay in the slowest portion of the RT distributions, captured by larger τ of the ex-Gaussian model of the RTs. Together, these findings supported our prediction that reduced inhibitory control in WM manifested as worse performance in the change

detection task for the 5-distractor condition than the 0-distractor condition under high physical load (30% MVC), which was more pronounced in older adults than younger adults.

These findings are consistent with some previous reports of negative interactions between cognitive and motor tasks in older adults, although these studies tend to use more demanding motor tasks (e.g., precision grip and gait) with significant involvements of cognitive control processes (Voelcker-Rehage & Alberts, 2007; Plummer-D'Amato et al., 2011, 2012). For instance, older adults exhibit altered gait when simultaneously completing a dual cognitive and motor task compared to performing the motor task alone (Plummer-D'Amato et al., 2011, 2012). Moreover, older adults tend to be negatively impacted by cognitive and motor dual-tasks, resulting in worse executive functioning performance (Voelcker-Rehage & Alberts, 2007). These previous findings could be accounted for by the direct competition for cognitive control mechanisms across the motor and cognitive tasks. In contrast, the present study has adopted a handgrip task requiring phasic isometric muscle contraction (Cain et al., 1971). It features voluntary and static contraction without muscle movement (and movement of hand and objects). This physical action is expected to require minimal executive control and involvements of control network as opposed to gait or precision grip tasks (Kobayashi-Cuya et al., 2018). Similarly, Park and colleagues (2021) adopted a handgrip task requiring phasic isometric muscle contractions and found that concurrent physical exertion affected visual attention and inhibitory control during a visual search task in young adults.

Nonetheless, older adults in the present study, exhibited decreased ability to inhibit distractors in the high physical load condition, providing strong evidence for inhibition-based theories of cognitive aging, which postulate that the ability to inhibit distracting information declines with age (Hasher & Zacks, 1988). More importantly, the decline in cognitive inhibition

in older adults seems amplified by the concurrent high physical load. This effect may be accompanied by an arousal-based enhancement effect (also see Park et al., 2021) which manifested as opposite patterns in μ and τ components of the ex-Gaussian analyses of the WM task RTs in the present study. It is however possible that the two effects may stem from the same neurocognitive mechanism. For example, physical exertion can yield heightened arousal which in turn increases norepinephrine released in the locus coeruleus (Nielsen & Mather, 2015). Its subsequent effect on cognition seems more pronounced in tasks involving executive functions (Mather & Harley, 2016; Mather et al., 2016). Therefore, arousal stemming from high physical exertion for older adults may result in increased distractor interference and speeded responses.

In addition to this novel theoretical significance, our findings that a simple physical task resulted in impaired cognitive control may be empirically important for understanding everyday functions of older adults. Daily functions may become difficult due to the negative interactions between cognitive and motor tasks, and consequently increases the risk of injury. Age-related declines in grip strength (e.g., Kallman et al., 1990) were not replicated in the present study. This is likely due to a large percentage of high functioning abilities of community subjects that volunteered for the experiment (i.e., a sampling bias). Consistent with this interpretation, older adults in the present study reported continued driving ability, which may indicate high functioning abilities and preserved grip strength since it has been previously reported that on average drivers apply roughly 31% maximum voluntary grip force on the steering wheel (Eksioglu & Kiziliaslan, 2008), as compared to 30% MVC at the high physical load condition in the present study. However, it is important to note that the current findings are expected to generalize across individual differences in grip and physical strength, given that the physical load

manipulation in the present study is operationalized as the proportion of individual MVC. Nonetheless, future research needs to recruit a more representative sample of older adults.

Using a novel paradigm, the present study demonstrated that concurrent effortful physical action can be detrimental to WM, especially in older adults. Reduced inhibitory control and physical abilities may pose a problem for the aging population, considering cognitive and motor actions are rarely engaged in isolation in everyday life, and moreover the various clinical populations with reduced grip strength in which the same physical activities can be more effortful. For example, grip strength is found to be reduced schizophrenic patients compared to healthy adults and is positively associated with WM (Firth et al., 2018). However, research on concurrent physical effort in relation to individuals' handgrip strength is still sparse. Future studies should examine the relationship between concurrent effortful physical action in other domains of cognition in healthy and clinical populations.

Funding

This work was supported by funding support from the National Institute of Mental Health (R01MH117132 to WZ).

Acknowledgments

WZ, WX, and LA designed the study. LA and WX collected data. LA and HP conducted data analyses. All authors contributed to manuscript preparation. Nonidentifiable data from all participants is available upon request from the corresponding author. Data collection was not preregistered.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Figures

Figure 1. Stimuli and procedure for the concurrent physical load and change detection task. Each trial began with a 4,000 ms screen prompting participants to grip the Hand Dynamometer at the indicated level (5% or 30% MVC) followed by the memory array containing zero-distractors or five-distractors (shown above). After a 900-ms delay interval, a test array was presented for 2,000 ms and participants were instructed to make a timed response within the 6,000 ms interval.

Figure 2. Three-way interaction with age group (younger vs. older adults), distractor size (0 vs. 5-distractors), and physical effort (5% vs. 30% MVC). (A) Accuracy results (K) for the change detection WM task. Cowan's K from trials with successful handgrip trials in the 0-distractor condition and the 5-distractor condition across MVC and age group. (B) The distractor interference effect (differences in K across the distractor conditions).

Figure 3. RT results for the change detection WM task. (A) Mean RTs from trials with successful handgrip trials in the 0-distractor condition and the 5-distractor condition across MVC and age group. (B) The distractor interference effect (differences in RT across the distractor conditions, see main text for details).

Figure 4. Posterior distributions of the three-way interactions (age group, distractor size, and physical effort) for each hierarchical Bayesian ex-Gaussian parameters. The posterior samples are fitted with a nonparametric kernel density function (solid black curves). The red triangles and the horizontal bars represent the means and 95% HDI of the posteriors of the interaction effects, respectively.

Table 1

Group-level posterior mean and 95% highest density interval (HDI) for each ex-Gaussian parameter (μ , σ , and τ) as a function of age, distractor size, and physical effort.

Parameters	5% Physical Effort		30% Physical Effort	
	0-Distractor	5-Distractor	0-Distractor	5-Distractor
Younger Adults (mean [95% HDI] in ms)				
μ	573.1 [560.6, 585.5]	591.7 [581.0, 604.3]	553.1 [541.7, 564.2]	580.4 [568.5, 592.7]
σ	82.1 [73.9, 91.9]	81.6 [73.1, 91.0]	75.4 [66.1, 83.6]	76.7 [66.8, 85.7]
τ	196.5 [181.1, 212.3]	244.3 [227.6, 260.2]	200.1 [185.1, 215.5]	232.4 [216.1, 250.3]
Older Adults (mean [95% HDI] in ms)				
μ	761.0 [738.0, 784.1]	834.8 [809.9, 863.5]	773.9 [751.7, 799.6]	783.5 [758.7, 811.6]
σ	118.6 [101.7, 137.3]	138.7 [120.5, 159.8]	123.8 [105.4, 142.1]	126.7 [108.7, 151.2]
τ	304.0 [273.8, 333.5]	290.2 [260.6, 326.1]	268.6 [239.0, 297.6]	367.0 [329.7, 404.5]

Supplementary Materials

Supplementary method: the ex-Gaussian model

The ex-Gaussian parameters were estimated by adopting a hierarchical Bayesian method (Rouder et al., 2005) with MatlabStan (Stan Development Team, 2016). With this approach we could estimate the grand mean of posterior parameter values at the population level, while simultaneously accounting for variabilities across subject, condition, age group, and trial levels using Markov chain Monte Carlo (MCMC) simulations. The main effects of each population-level ex-Gaussian parameter were estimated using a general linear model, sampling from the Normal distribution. In this model, the mean is a sum of the fixed effect (condition-effect, age-effect, and condition-by-age interaction) and the random effect (individual-level), and the variability describes the individual-by-condition-by-age interaction effect. We chose reasonable to non-informative priors for all parameters to cover all plausible RT effects (e.g., 0-5 s) to minimize biases in posterior distribution due to the choice of priors.

Supplementary Table 1. *Sample Demographics.*

Characteristics	Younger Adults	Older Adults	t/χ^2	df	p
	Mean (SD)/%	Mean (SD)/%			
Age (years)	20.35 (2.31)	72.37 (5.04)	-	-	-
Gender					
Female	54.80%	47.40%	.38	1	.539
MVC	149.47 (65.78)	160.37 (57.83)			
Female	126.93 (52.01)	163.21 (64.49)	-.44	47	.664
Male	176.84 (72.00)	157.82 (54.60)			
Years of Education	14.08 (1.38)	15.18 (2.19)	1.85	41	.077